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Comparison of Planer Dose Equilibrium and Computed Tomography Dose Index and Implications for Reported Patient Dose Information

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Abstract

Technical developments are ongoing in CT, and there has been a continually increasing trend in patient prescription, resulting in increased exposure. Currently, doses delivered during CT are generally evaluated using computed tomography dose index (CTDI), which is measured with a 10 cm pencil ionization chamber placed in a 14 cm PMMA phantom. However, shortfalls in CTDI have been identified by the American Association of Physicists in Medicine (AAPM) who have proposed a new method, dose equilibrium (DEq). In this paper, the dose equilibrium was used to estimate the dose in two protocols (thoracic and abdominopelvic) and compared to CTDI values. In addition, a retrospective correction was applied to 20 patient CTDI's by characterizing the specific DEq profile of the system scans. The results indicated the dose equilibrium estimations of two protocols, thoracic and abdominopelvic, were 29% and 30% respectively, higher than those informed by the CT scanner. In addition, a retrospective dose correction estimation of a random sample of twenty patients demonstrated an annual underestimation in absorbed dose by between 26% and 28%. Continued use of the CTDI method in quality assurance of modern CT could result in greater patient risk. AAPM Task Group 111 presents a more accurate, safer method to estimate dose and its adoption is paramount.

Keywords

CT Dosimetry, CTDI Method, DEq Method, CT Scanner

1. Introduction

Computed Tomography (CT) comprises approximately 5% of global medical X-ray procedures [1]. However, the dose from CT accounts for 34% of the yearly dose for the population from all medical X-ray imaging procedures worldwide [1]. This is not unexpected due to the high dose per examination in CT procedures [2].

The absorbed doses result from primary radiation as well as scattered radiation. Moreover, Computed Tomography Dose Index (CTDI) is used to determine CT quality assurance (QA) measurements and dose measurements, being the absorbed dose along the longitudinal axis (z-axis) during a single X-ray source rotation [3]. This measurement is usually conducted in a cylindrical phantom using a 100 mm ionization chamber. However, the chamber is responsible for a significant error in the dose profiles as it does not take into account some of the radiation scattered beyond the relatively short (100 mm) range of integration along the z-axis [4] [5]. This is mostly due to over-beaming in multi-slice CT, where the z-collimation of the source radiation is broadened to achieve umbra-region incidence uniformly across detectors.

Due to the increase of the detection system size along the z-axis, CT beams became larger, and much of the radiation not utilized by the detectors is incident on the patient. The more recent generations of CT scanners provide helical scanning mode or cone-beam irradiation geometries; however, the pencil chambers in these scenarios are too short to measure the radiation completely.

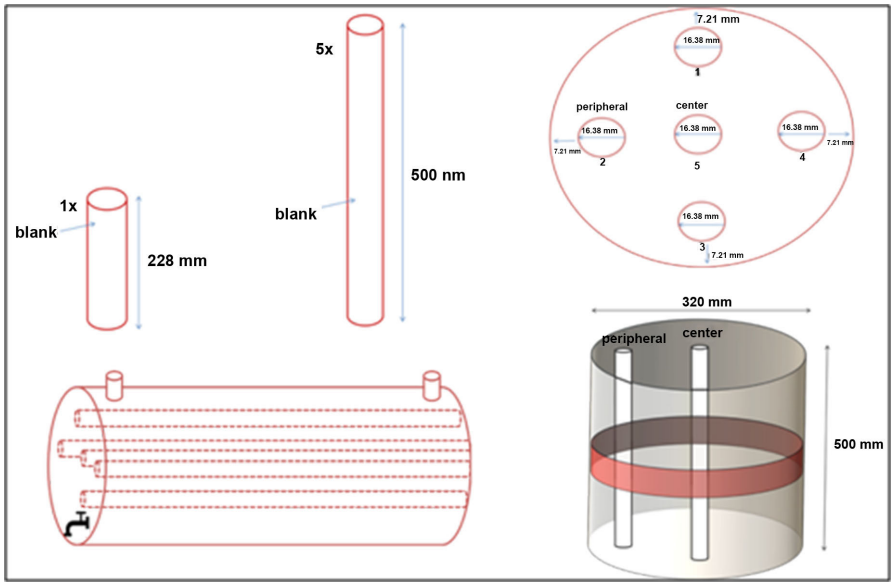
The AAPM Task Group Report No. 111 [6] outlined a new method of measurement derived from CTDI using a small volume ionization chamber in a cylindrical water phantom that is long enough to determine dose equilibrium. With this dose equilibrium (DEq) measurement, we acquire a value sufficiently equivalent to both the primary and scatter radiation present from the beam [6].

The aim of this study is two-fold. The first is to use the AAPM dose equilibrium (DEq) method [6] [7] to estimate the dose values, and then compare it to CTDI values. The second is to retrospectively correct twenty random anonymous patient records of CTDI with new DEq estimates over the course of a year.

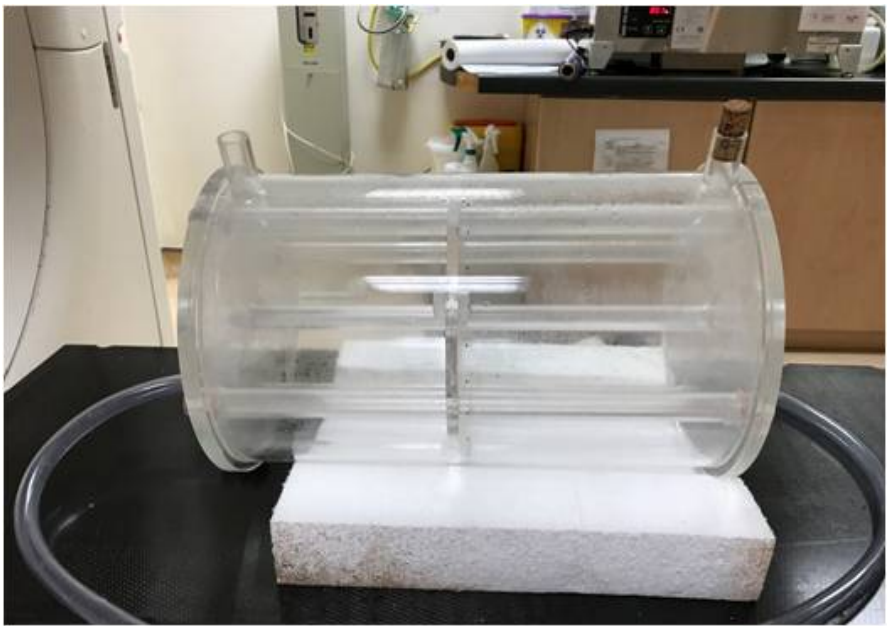
2. Materials and Methods

This study used a Toshiba CT scanner, Aquilion 16, a third-generation multi-slice helical CT scanner, a 60-kW generator, a 7.5 MHU tube.

The DEq phantom was built in-house [8] using a water-filled phantom (**Figure 1**) based on the work of Dixon and Ballard [9] [10]. It is 32 cm in diameter and 50 cm in length, with a centre hole and four peripheral holes. Perspex blanks were placed in the holes when not in use. This chosen phantom size represents the attenuation and absorption characteristics for an average adult. The material composition of the phantom was based on IAEA TRS 277 [11] (**Figure 1**). And the small ion chamber (Farmer chamber PTW type 30013) was used with the DEq phantom to calculate dose.



(a)



(b)

Figure 1. (a) Schematic of DEq phantom and (b) the actual DEq phantom.

The collection volume of the Farmer chamber, which was calibrated by the National Standards of the German National Laboratory, was 0.6 cm^3. In addition, a Sun Nuclear PC electrometer, equipped with a cable that allowed it to be placed outside the scatter-radiation field so as to avoid extraneous currents, was used with the chamber to provide a bias voltage of ±300 V.

Thoracic and abdominopelvic clinical protocols were chosen to measure DEq and CTDI. **Table 1** provides the scan parameters for kV, mA, rotation time, slice thickness and pitch used in this study, while the scan length for each protocol was 450 mm.

Table 1. Summary of scan parameters used for the examination of thoracic and abdominopelvic protocols.

Protocol	Scan Mode	kV	mA	Rotation/Sec	Thickness (mm)	Number of Slices	Pitch
Thoracic	Helical	135	150	1	4	4	0.6
Abdominopelvic	Helical	120	100	1	4	4	1

2.1. The Planer Average Equilibrium Dose Measurement and Comparison with CTDI Value Measurement

A detailed DEq phantom characterization and comparison to CTDI has previously been reported [8] The DEq method uses an upper limiting value based on the scanning length (L) and the cumulative dose ($D(0)$). There is a direct relationship between the scanning length (L) and the cumulative dose at z = 0, along with accumulating contributions from the outlying scan sections, until an upper limiting value is reached and the scatter radiation produces negligible contributions [6] [8] [12]. The equilibrium dose (DEq) is given by [6] [7] [8] [13] [14]

$$DEq = D(0)/h(L). \quad (1)$$

(where $h(L)$ is approach to equilibrium function, $h(L) = 1$ when L becomes large enough to yield scatter equilibrium at $z = 0$) [6]. In this study, the equilibrium dose was determined for the centre, and peripheral axes for the two protocols (**Table 1**), with the planer average equilibrium dose then determined using Equation (2) [6] [7] [8] [13] [14]

$$DEq = 1/2DE_{q\cdot\text{center}} + 1/2DE_{q\cdot\text{peripheral}}. \quad (2)$$

The planer average equilibrium dose was compared to CTDI values which have been obtained from the readout of the CT scanner. CTDI uses a pencil-type ionization chamber that has a 100 mm active length and is inserted into the phantom's holes to measure the dose by taking a single rotation without table movement [15] [16] This allows the assessment of the weighted CTDI ($CTDI_w$) and the volumetric CTDI ($CTDI_{vol}$) [15] [16] [17].

2.2. Correction of Past Patient Data to Dose Equilibrium

$CTDI_{vol}$ reports for the procedures and rescans performed throughout the year of a random sample of twenty anonymous patients were extracted. Using the lookup table (**Table 2** and **Figure 2**) characterizing our specific CT system, the patient-specific $CTDI_{vol}$ was retrospectively corrected to DEq.

To apply the correction, we measure the DEq and $CTDI_{vol}$ at varying clinically relevant kV and mA ranges (as shown in **Table 2**). DEq was plotted against $CTDI_{vol}$, and a linear regression was fitted to extrapolate a standard fit to estimate DEq measurements for any given $CTDI_{vol}$ within the range (**Figure 2**).

From this linear regression, the DEq can be estimated from a given $CTDI_{vol}$ within a standard CT range for our specific CT system allowing for the retrospective correction of past patient reported $CTDI_{vol}$ for this specific scanner.

Table 2. CTDIvol versus DEq with different kV and mA.

kV, mA	CTDIvol (mGy)	DEq (mGy)
kV 80, mA 5	2.4	3.1
kV 80, mA 100	5.2	6.9
kV 80, mA 250	12.9	16.2
kV 100, mA 150	14	17.7
kV 100, mA 250	23.3	29.1
kV 120, mA 200	28.3	35.2
kV 120, mA 250	35.4	46.2
kV 100, mA 500	46.5	58.4
kV 135, mA 250	47.3	59.4
kV 120, mA 500	70.9	89.2

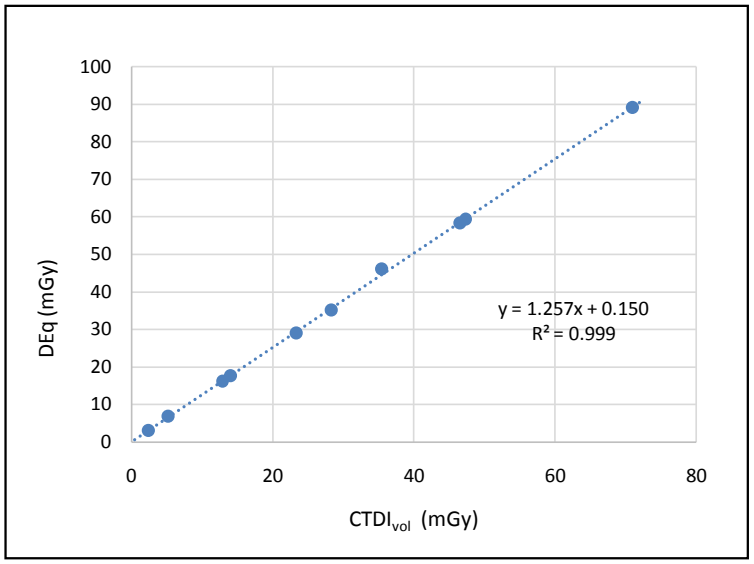


Figure 2. DEq and $CTDI_{vol}$ linear regression.

3. Results and Discussion

3.1. Comparison between Planer Average Equilibrium Dose and $CTDI_{vol}$

The DEq measurement was compared to the $CTDI_{vol}$ measurement for both the thoracic and the abdominopelvic protocols, as shown in Table 3. The DEq for the thoracic protocol was 54.7 mGy, while the $CTDI_{vol}$ was only 42.5 mGy. The difference in these measurements represents a variation of 29%. For the abdominopelvic protocol, the DEq measurement was 15.7 mGy, while the $CTDI_{vol}$ was only 12.1 mGy. The difference in these measurements represents a variation of 30%, which is similar to the percentage variation seen in the thoracic dose measurements. These results indicate that in both cases, the dose delivered was underestimated when using the CTDI method [5] [9].

Table 3. The planer average equilibrium dose measurement and comparison with CTDI volume.

Method	Thoracic (mGy)	Abdominopelvic (mGy)
DEq	54.7	15.7
$CTDI_{vol}$	42.5	12.1
Variation	29 %	30%

3.2. Correct Past Patient Data to Dose Equilibrium

The $CTDI_{vol}$ lookup table was used to estimate DEq for the performed procedure (**Table 2**, **Figure 2**). This revealed that over the course of several scans, our random patient sample in **Table 4** received an absorbed dose anywhere from 4 mGy up to 13 mGy greater than previously estimated by $CTDI_{vol}$.

Table 4 illustrates the total of 20 patients that were used to compare estimations of absorbed doses from both CTDI and DEq over a period of one year. The study consisted of 9 females and 11 males with an average age profile of 30 years ± 15 years. Two patients received one scan, twelve received two scans, three received three scans, and three received four scans. The CTDI volume estimates ranged from a low of 14.9 mGy to a high of 49.3 mGy, while the DEq estimates ranged from a low of 19.0 to a high of 62.3 mGy. The differences between the two methods ranged from 4.1 mGy to 13 mGy, with the DEq estimates being consistently higher than the CTDI volume estimates. Furthermore, when expressed as a percentage, the DEq estimates were 26% to 28% higher in all cases. Therefore, the $CTDI_{vol}$ method significantly underestimated the absorbed dose when compared to the DEq method for all patients.

An example of an individual male patient undergoing prostate imaging is shown in **Table 5**, broken down by each scan as well as summed over all scans performed throughout the year. This process was performed for all patients among the sample who's scan protocol was torso or pelvic.

Patient 4 received four scans and the system output was estimated for both $CTDI_{vol}$ and DEq. In scan 1, the $CTDI_{vol}$ was estimated at 2.9 mGy while the DEq was measured at 3.8 mGy, a difference of 31%. In scan 2, the $CTDI_{vol}$ was estimated at 6.2 mGy while the DEq was measured at 7.9 mGy, a difference of 27%. Scan 3 measurements also produced a difference of 27%, with the $CTDI_{vol}$ and DEq at 24.1 mGy and 30.5 mGy, respectively. An identical difference of 27% was calculated for Scan 4, with the $CTDI_{vol}$ and DEq at 10.4 mGy and 13.2 mGy, respectively. For all four scans, 43.6 mGy was the total for the $CTDI_{vol}$, and 55.4 mGy was the total for the DEq. In all instances, the CTDI values underestimated the dose as compared to the DEq measurement. Moreover, it was consistently underestimated, with three out of four scans producing a difference of 27%, and the fourth producing a difference slightly more at 31%. The total of all four scans was in the same range at 28%.

Table 4. Patient date set with updated estimated of absorbed doses.

Patient number	Number of scans	CTDI volume (mGy)	DEq (mGy)	Absolute difference (mGy)	Percentage difference
Patient 1	3	26.4	33.6	7.2	27%
Patient 2	2	49.3	62.3	13	26%
Patient 3	2	16	20.4	4.4	28%
Patient 4	4	43.6	55.4	11.8	28%
Patient 5	2	14.9	19.0	4.1	28%
Patient 6	2	27	34.3	7.3	27%
Patient 7	2	32.1	40.7	8.6	27%
Patient 8	2	19	24.2	5.2	27%
Patient 9	1	15.8	20.0	4.2	27%
Patient 10	2	39.6	50.1	10.5	27%
Patient 11	2	18	23.0	5	28%
Patient 12	4	25.7	33.0	7.3	28%
Patient 13	2	14.9	19.0	4.1	28%
Patient 14	3	36.3	46.1	9.8	27%
Patient 15	3	39.4	50.0	10.6	27%
Patient 16	4	25.1	32.2	7.1	28%
Patient 17	2	18.8	24.0	5.2	28%
Patient 18	2	16.8	21.4	4.6	27%
Patient 19	2	29.4	37.3	7.9	27%
Patient 20	1	18.2	23.0	4.8	26%

Table 5. Patient 4 absorbed dose updated.

Patient number	Scan	CTDI volume (mGy)	DEq (mGy)	Percentage difference
Patient 4	1	2.9	3.8	31%
	2	6.2	7.9	27%
	3	24.1	30.5	27%
	4	10.4	13.2	27%
Total		43.6	55.4	28%

4. Conclusions

With the new generation of CT scanners, utilizing helical scanning mode and increased beam width and depth with associated increased detector size, the use of CTDI is no longer appropriate. With an average absorbed dose underestimation of 27% [5] [8] for all patients compared to that of DEq. The continued use of CTDI in dose estimation presents a greater risk to patient safety.

From the experimental results, $CTDI_{vol}$ values, as informed by the CT scanner,

were lower than planer average equilibrium doses (DEq) values for both protocols, determined in agreement with AAPM TG111, differences ranged between 29% and 30%.

In addition, the absorbed dose estimated for a sample of patients was underestimated by CTDI when compared to DEq by between 26% and 28%. The systemic underestimation of absorbed dose leaves both patients and staff misinformed and at greater risk.

In conclusion, it can be seen from the results that the characterization of dose through the use of CTDI is insufficient and inaccurate for modern CT machines. The results exhibited significant error in the characterization of dose profiles and implementing the new method outlined by the American Association of Physicists in Medicine Task Group report No. 111 [6] is a key to a more accurate characterization of the dose profiles from modern CT scanners. This method is relatively simple to follow and can be adapted to different phantom designs to determine DEq. The DEq method, therefore, is a simple, standardized measure of the dose output of the CT scanner that can be used for quality assurance.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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